Renewable and Sustainable Energy Reviews 16 (2012) 1735–1744

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Assessment of world lithium resources and consequences of their geographic distribution on the expected development of the electric vehicle industry

Camille Grosjean[a,*], Pamela Herrera Miranda[a], Marion Perrin[a], Philippe Poggi[b]

[a] National Institute of Solar Energy, Department of Solar Technologies, Laboratory of Electricity Storage, INES-RDI, BP 332, 73377 Le Bourget-du-Lac, France
[b] University of Corsica Pasquale Paoli, Laboratory of Physical Systems for the Environment (SPE), UMR CNRS 6134 CNRS, Vignola, Route des Sanguinaires, 20000 Ajaccio, France

ARTICLE INFO

Article history:
Received 25 October 2011
Received in revised form 8 November 2011
Accepted 9 November 2011
Available online 18 January 2012

Keywords:
Lithium
Electric vehicle
Lithium-ion battery
Pegmatite ores
Brines

ABSTRACT

Electric vehicles (EVs) are on the verge of breaking through, most presumably flooding the automotive market with lithium-ion batteries as energy storage systems. This paper investigates the availability of world lithium resources and draws conclusions on its actual impact on the EV industry. Apart from lithium deposits geographic distribution, our contributions to the global knowledge range from a short-term forecast of lithium price evolution to a picture of the existing lithium industry and market plus a detailed explanation of the geologic origins of all the inventoried lithium resources.

Contents

1. Introduction

In the context of fossil fuels depletion and climate change pending threats, expectations for cleaner and more sustainable transport solutions are being embodied in electric vehicles (EVs). Since no standard was agreed on, various energy storage system (ESS) technologies are still being tested to propel EVs. Among them, lithium-ion batteries (LIBs) emerge as the most presumptive candidate, for they offer high energy/power densities meeting EV application specific requisites. So far, much attention was paid by researchers either to the improvement of materials synthesis routes and performances or to EV grid and social integrations, e.g. studies on battery swapping stations, fast-charging systems, vehicle-to-grid (V2G) implementation, etc. But still, the future evolution of lithium prices and the very abundance of raw materials necessary to feed the EV market with LIB has raised until now little interest among the scientific community whereas it has found a significant worried echo in the media.

The concept of EV came back in the late 1990s and with it the idea of using new promising lithium batteries as ESS. At that time, an assessment of past, current, and future trends of lithium market was achieved by Nicholson and Evans [1]. Geologist by profession, Evans was one of the first witnesses of lithium business emergence as he became involved in the Bikita mining campaigns in the early 1970s. From then on, he made it a point of honor to actualize the inventory of world lithium resources [2–6]. With Kunasz [7–9], another veteran lithium geologist, the way was paved for further

* Corresponding author.
E-mail addresses: camille.grosjean@cea.fr, c.grosjean@laposte.net (C. Grosjean), marion.perrin@cea.fr (M. Perrin), philippe.poggi@univ-corse.fr (P. Poggi).

1364-0321/$ – see front matter
doi:10.1016/j.rser.2011.11.023

market analyses and inventories whose publication rhythm echoed the fluctuating importance of lithium trade [10–17].

Due to the very uncertainty existing around the resources amount accessible for industrial purposes, the question of lithium availability firstly arouse very early in its history, as lithium was investigated for energy applications [18]. Before raising interest with its possible use to produce tritium as a fuel for fusion energy [19], lithium was already coveted for EV applications. In 1996, Will [20] was indeed the first to wonder about the availability of lithium for any industrial application. His study was though too much anchored in the economy, missing the points of geology and geostrategy. Besides, the whole lithium industrial structure has changed since then. Tahil [21,22] exploited more recent data and concluded that using lithium for EV was not a sustainable choice since world lithium production appeared insufficient to cover the needs of the EV industry. On the contrary, after applying to lithium the “cumulative availability curve” method they had experimented on copper, Yaksic and Tilton [23] concluded that depletion would not threaten lithium given its promised cheap extraction from seawater. In their wake, Gruber and Medina [24] went deeper in the reasoning by confronting major reference sources and by evaluating the precise lithium content of all deposits. In parallel, Clarke and Harben [25] created a map on the basis of such data, turning what yet stood as science into geoeconomics.

This review means to assess the worldwide availability of lithium resources in a new way, confronting updated resources data with the trade reality, especially the lithium market shares and prices evolution, which enables to draw conclusions and foresee their impact on future EV prices. Special focuses are made on the geological origin and nature of all kinds of lithium resources and on the current structure of the lithium industry. Eventually, salient geostrategic bottlenecks following from resources geographic distribution are discussed and perspectives are given to cope with the emerging problems.

2. Forecast evolution of lithium prices and consequences on the EV industry

When the oil industry is on the verge of collapsing because of declining reserves and increasing prices, the common sense of people hearing that oil-dependent internal combustion engine (ICE) vehicles will be replaced by LIB-propelled “electric” vehicles induces them to wonder – among other questions – if there will be enough lithium on the planet to feed the whole automotive market and at a price remaining steadily low or so. To start this study, we found important to determine roughly whether the lithium price is susceptible to raise the price of EV batteries at a non-affordable level for end-users, i.e. EV drivers and buyers.

Aiming at forecasting the future trends of lithium price and comparing them with the expected battery prices, we used past evolutions of lithium commodity prices between 1970 and 2010 (Fig. 1 [26]) as inputs for an econometric modeling. Thanks to the Box & Jenkins methodology, we identified and evaluated the dynamic model of price series by using normality, white noise and Dickey–Fuller tests. As we realized that the stationary condition was not satisfied, we differentiated the price series to turn it into a stationary one (Fig. 2). Then, correlation analysis enabled us to pinpoint difference series as an ARIMA(1,1) model characterized by a significant first peak and a sinusoidal behavior (Fig. 3). Eventually, with ε standing for residues and t for time, i.e. the year considered, the model expression is:

$$price_t - price_{t-1} = 0.032 + 0.164 price_{t-1} + \varepsilon_t + 0.157 \varepsilon_{t-1}$$

This modeling enables us to predict future lithium price values (Table 1). As a result, lithium price is expected to be multiplied by five within ten years from 5.42 in 2010 to 25.50 $/kg in 2020, and this with an annual growth rate which appears to slowly decrease along time from 17.2% to 16.5%.

Lithium price future evolution is a precious input for later calculations meant to assess the impact of lithium prices on EV prices, when progressive battery cost reductions are taken into account (Table 1). With an annual cost reduction postulated on the basis of a potential economy of scale and estimated to $100 between 2010 and 2012 and $50 between 2012 and 2020, we arbitrarily

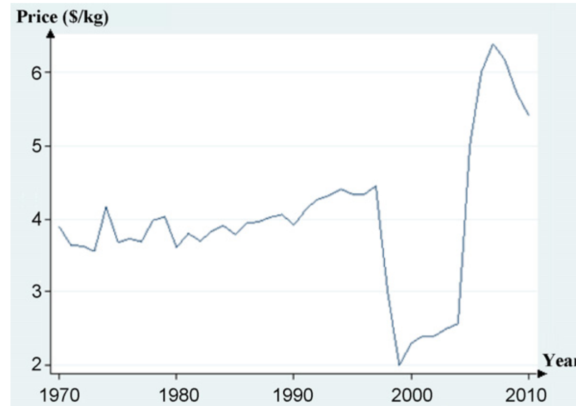

Fig. 1. Non-stationary evolution of lithium price series 1970–2010 [based on “Lithium statistics” from the United States Geological Survey, 2010].

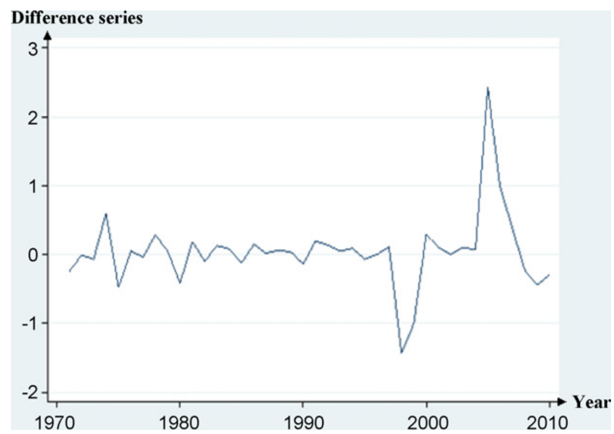

Fig. 2. Stationary difference series obtained after price series differentiation [based on our own works].

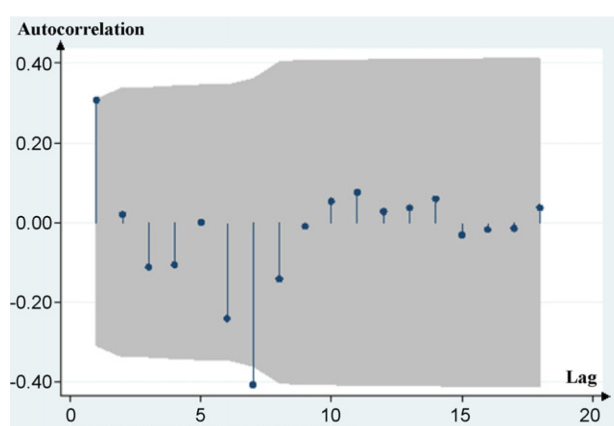

Fig. 3. Autocorrelation diagram of difference series typical of ARIMA(1,1) [based on our own works].

Table 1
Forecast of lithium costs and shares in the price of EV batteries (2010–2020) [own works].

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Lithium price [Econometric model ARIMA(1,1)] ($/kg)	5.42	6.35	7.40	8.60	10.13	11.82	13.80	16.10	18.77	21.88	25.50
Lithium price for battery (hypothesis: LCE = 0.6 kg Li/kWh) ($/kWh)	3.25	3.81	4.44	5.16	6.08	7.09	8.28	9.66	11.26	13.13	15.30
Lithium cost in HEV battery (hypothesis: Capacity = 2 kWh) ($)	6.50	7.62	8.88	10.32	12.16	14.18	16.56	19.32	22.52	26.26	30.60
Lithium cost in PHEV battery (hypothesis: Capacity = 7 kWh) ($)	22.76	26.67	31.08	36.12	42.55	49.64	57.96	67.60	78.83	91.90	107.10
Lithium cost in EV battery (hypothesis: Capacity = 25 kWh) ($)	81.30	95.25	111.00	129.00	151.95	177.30	207.00	241.44	281.55	328.20	382.50
Battery price forecast [Crédit Suisse] ($/kWh)	1100	1000	900	850	800	750	700	650	600	550	500
HEV battery price forecast (hypothesis: Capacity = 2 kWh) ($)	2200	2000	1800	1700	1600	1500	1400	1300	1200	1100	1000
PHEV battery price forecast (hypothesis: Capacity = 7 kWh) ($)	7700	7000	6300	5950	5600	5250	4900	4550	4200	3850	3500
EV battery price forecast (hypothesis: Capacity = 25 kWh) ($)	27,500	25,000	22,500	21,250	20,000	18,750	17,500	16,250	15,000	13,750	12,500
Lithium share in battery price (%)	0.30	0.38	0.49	0.61	0.76	0.95	1.18	1.49	1.88	2.39	3.06

reduce the global cost of EV batteries, but as lithium unit quantity is conserved, we also arbitrarily enlarge the share of lithium in this global cost of EV batteries. But still, even by doing so, the corresponding lithium share only increases from 0.30% to 3.06%, thus suggesting that the economic impact of a fivefold-increased lithium price is still acceptable for EV buyers hence for EV market penetration.

Looking back at the past evolution of lithium prices (Fig. 1), one can be surprised by the apparently erratic behavior of the curve, as lithium price remains stable from 1970 to 1990 before fluctuating alternatively upward and downward with particularly sharp peaks in 1997 and 2008. These variations are linked simultaneously to the structure of lithium industry and to the end-use sectors in which lithium is consumed; a consequence of the trade imbalance between offer and demand, somehow. From 1970 to 1990, a few industrials exploited hard rock minerals as a source of lithium under the form of mineral concentrates for the glass and ceramics industry, mostly in Australia and the United States but also in Portugal and Spain. As such rare applications were non-captive, prices were stable. Little by little, though, the German firm Chemetall bought all the small dispersed companies that were mining lithium-rich ores throughout the world, thus forming a monopoly. This fact explains the slow increase of lithium price observed from 1990 to 1996. From 1997 on, the way of extracting lithium fundamentally changed with the appearance of salt lake brines exploitation for lithium carbonate sales. From 1997 to 2000, the Chilean company SQM (=Chemical Mining Society) became market leader thanks to very low production costs, obliging by the way many hard-rock-exploiting sites to close. Applications also changed with the development of lithium batteries in mobile applications and the will of aviation and car industries to lighten their products with lithium-containing aluminum alloys. From 2005 to 2006, a slight increase of the price is noticeable due to a trade bottleneck caused by production problems in the Chilean salt lake of Atacama and a concomitant increase of the captive battery demand. Presumably because of the soaring price of oil, the average exportation cost of lithium also rose sharply from 2007 to 2008 till reaching a 6.4 $/kg record value. More recently, the economic crisis affected most of the lithium users who accordingly restrained their consumption.

Analyzing lithium price evolution is packed with information. So, to perfectly understand what is at stakes with lithium availability for the EV industry, we must decompose things: on the one hand, the lithium market and EV industry particular needs; on the other hand, the structure of lithium industry.

3. Lithium market compared to EV particular needs

There are plenty of lithium-based products on the market. As shown in Fig. 4 lithium carbonate (Li_2CO_3), mineral concentrates and lithium hydroxide (LiOH) are lithium most common commercial forms, standing for 80% of market shares [17]. Mineral concentrates are raw materials directly involved in ceramics or glass production whereas lithium carbonate and hydroxide are chemically processed ingredients mainly used in secondary batteries, greases, aluminium alloys, etc. Surprisingly, the major application of lithium products in 2007 was in the ceramics and glass industry with 37% of market share against 20% for batteries [25]. As far as LIBs are concerned, lithium is mostly contained in positive electrodes (90%) and electrolytes (9%) [17]. However, its yet scarce utilization in negative electrodes may soon evolve with the increasing interest for lithium titanium oxide (LTO) materials.

Apart from mineral concentrates which can be used in their raw form, all lithium-based commercial products appear to be chemical derivatives of lithium carbonate. In the rest of this paper, the study of lithium and EV industry will thus be reduced to that of lithium carbonate production and consumption.

In 2009, only 80 t of lithium carbonate were reported to form stockpiles in South Korea [27]. As such, the global lithium production can be assimilated to that of global consumption whose progression is constant with 12,500 tons (t) produced in 1998 [1], 20,340 t in 2005 [12], and 21c300 t in 2008 [25]. Looking at the

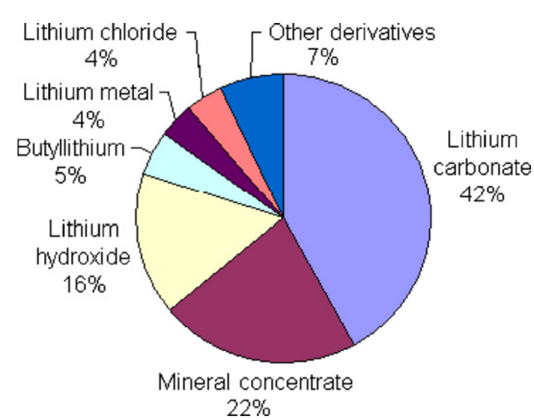

Fig. 4. Market shares of lithium-based commercial products. Based on data from Roskill [17].

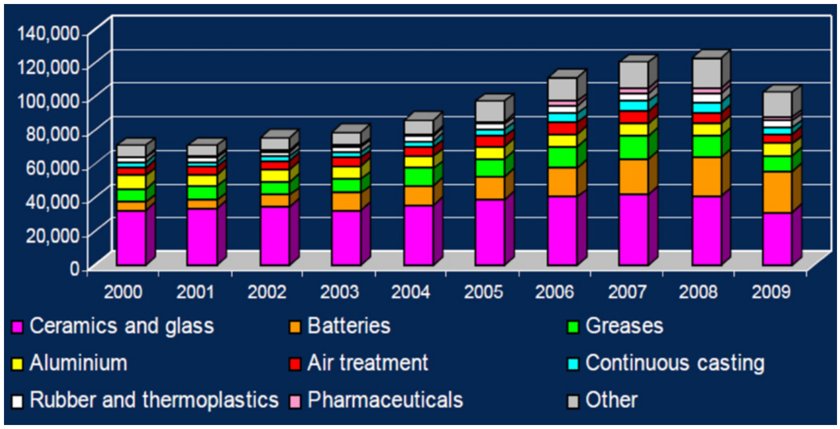

Fig. 5. Recent evolution of lithium carbonate demand by applications. Roskill [17].

historical evolution of global lithium carbonate demand (Fig. 5 [17]) an average annual growth rate of 6% is observed between 2000 and 2008 before a sudden fall caused by the economic crisis of 2009. The same figure is very informative on the lithium dependence of all end-use application sectors. Lithium demand from both batteries and aluminium branches appears to keep on growing even during the very period of crisis, thus representing an artificially bigger proportion of lithium end-use. In all likelihood, and as predicted by other studies dealing with its world market forecast [16], lithium will thus be replaced or abandoned in most of its current applications, except for batteries whose extremely captive use will undoubtedly put the LIB industry into a first-rank consumer position. This is all the truer since the figures we relied on are only representative of the lithium used in batteries for portable electronic devices. This becomes critical when we think that the future lithium demand of millions of EVs will be added to this already existing captive lithium consumption.

Considering that a LIB contains 8% Li_2CO_3 wt. and that packs of batteries will at least weigh 200 kg in future EVs, a minimum of 16 kg of lithium carbonate would be required for each pack of batteries. For the whole annual lithium production of 21,300 t, it means that a maximum of 7.1 million packs of batteries can be annually fabricated, considering that EV LIB fabrication monopolizes all the market. There are presently more than 1 billion vehicles running in the world and a total of 65 million new vehicles are registered each year [28]. So, if we consider the market share of 25% for batteries, the lithium is only available for a shrunk figure of 2 million packs of batteries which now hardly represents 3% of the new vehicle registrations. As a result, the current annual lithium production stands out clearly insufficient to quickly provide a future EV market with LIBs. The question is henceforth to know if the lithium industry is able to raise the levels of production and at which price. Studying the current lithium production structures, processes and resources gives significant clues to answer this.

4. State-of-the-art of the lithium industry

Lithium carbonate is today mostly fabricated by mining, extracting and treating two main resources: spodumene ores and salt-lake brines. The way they are exploited is detailed and compared hereafter.

Spodumene is a lithium-rich ore contained into a special type of stone called pegmatite. Historically, it was the first resource exploited to produce lithium at an industrial scale but it is now only extracted in a few places, mostly in the mine of Greenbushes (Australia), often as a by-product of rare earth elements (REE) such as tantalum (Ta) or niobium (Nb), or of other elements like rubidium (Rb) and cesium (Cs). In such pegmatite hard-rock minerals, lithium contents (1–4%) and recovery rates (60–70%) are high, thus allowing a good profitability of the mining sites. However, they are made challenging to exploit due to the hardness of their gangue and inner material plus the tough access to the belt-like deposits that host pegmatite veins. All steps of exploration, probe drilling, sample analysis, and process testing pave the way for a complex but usual mining process consisting in digging pits, excavating tons of rocks and having them thermochemically treated in a nearby factory. Based either on an acid lixiviation or a soda ash synthesis route, the treatment of hard-rock minerals like spodumene is short (i.e. five days long) and constantly productive throughout the year. However, it requires the use of energy-consuming high furnaces and rock-crushing devices in addition to the usual polluting fuels and concentrated chemicals. Concerning financial aspects, mining process and facilities require huge investments. The cost for their enlargement is however more affordable for it only consists in increasing excavators and trucks rate of production. Mining thus appears very advantageous as it can fit a potential growth in lithium demand. Its backwards are the environmental damages caused by pit-digging machines, plus the pollution involved in the processing chain turning excavated raw minerals into ready-to-sell lithium carbonate.

Salt lake brines are water resources with high concentrations of mineral salts. They are reachable either at the surface or not deep in the ground of lake-like saline expanses located in particularly dry areas whose climate special conditions allow salts persistence. Such an area is also called salar, from Spanish. Amidst other elements, salt lake brines contain lithium but their lithium grades are low (0.017–0.15%) and vary a lot, between different salars (Table 2 [29]) but also between the different areas of a same salar (Fig. 6 [30]). As a result, the initial phase of resource estimation which is subservient to any deposit exploitation is a very long-lasting process based on grid-shaped salt crust and core samplings, chemical analysis, precipitation tests, and pilot plant operations. It delays any subsequent action for two to three years. As regards the extraction process, it is very simple and environment-friendly as it only relies on having brines pumped and evaporated under solar natural effect. From one decantation pond to the other, it is still a long series of time-consuming steps. Gradually, the decantation basins show a higher lithium grade and their color visibly tends to blue as the other salts in presence are taken out after precipitation. Once production facilities are settled and ready to run, it lasts between one to two years until the processed lithium carbonate is ready to be sold. It can last even longer in regions submitted to the effects of winter for the evaporation process is put back. It is being the case in a few developing deposits in Tibet, China. Such a long extraction

Table 2
Diversity of brines composition in mineral salts for various salars.

(a)

Country	Salar or lake	Li	Mg	K	Na
Chile	Salar de Atacama	0.15	0.96	1.80	7.6
Bolivia	Salar de Uyuni	0.096	2.0	1.67	9.1
Argentina	Salar del H ombre Muerto	0.062	0.089	0.61	10.4
United States	Great Salt Lake, UT	0.006	0.8	0.4	7.0
	Salton Sea, CA	0.022	0.028	1.42	5.71
	Searles Lake. CA	0.0083	0.034	2.30	15.20
	Silver Peak, Nev	0.03	0.04	0.6	6.20
Israel-Jordan	Dead Sea	0.002	3.40	0.6	3.00
China	Lake Zabuye	0.097	0.001	2.64	10.80

(b)

Salar	Hectares	Samples	Li (ppm) up to	K (ppm) up to
Salar Grande	4000	4	123	2770
Piedra Parada	1500	14	103	2040
La Isla	16,500	19	1080	10,800
Agua Amarga	3100	6	157	2490
Las Parinas	5400	7	477	7820
Aguilar	8800	3	337	3990
Maricunga	104	18	916	11,400
Total	39,404			

(a): "Lithium and lithium compounds" [29]; (b): Salares Lithium Inc.

process stands out quite unsuited to possible sudden change in lithium demand.

Huge quantities of lithium are contained in oceans and seas. However, its concentration is so small (170 ppb, i.e. parts per billion) that it would be industrially complex and costly to isolate lithium amid the other seawater mineral salts. There is only one Japanese laboratory working on the topic [31] but even after years of improvement and although they obtain a very high quality lithium, their process still leads to a production cost of 80 $/kg, i.e. much more than salt lake brines (2–3 $/kg) or spodumene (6–8 $/kg).

Despite simple, cheap, and environment-friendly processes, the lithium carbonate production from salt lake brines shows important drawbacks as regards low lithium grades, high dispersions of composition, uncertainty of recovery rate and very long durations necessary either to build new production facilities or to enlarge existing ones. It is furthermore subservient to the settling of workers and the transportation of the obtained product in and from isolated desert-like regions. Lithium extraction from hard-rock minerals is more secure with good lithium grades, high recovery rates, and quick process durations that make it way more suited to any market change. However, the mining damages and thermochemical processes involved are costly and may represent a heavy load for the environment in terms of landscape damage and pollution. No matter how different their production costs are, both technologies of lithium mining, extraction and treatment from spodumene ores and salt lake brines are likely to play an equally important role in the near future. Apart from seawater, there is room for other conceivable resources that show good potential for lithium production and thus lately raised interest.

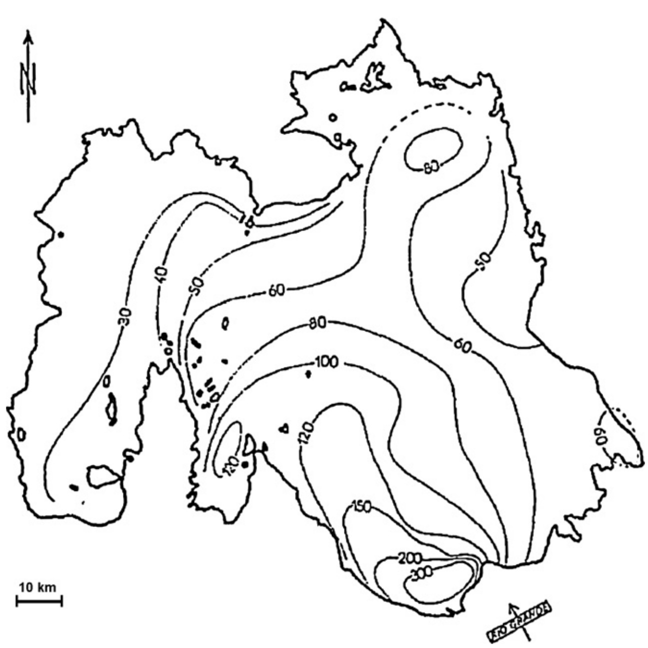

Fig. 6. Example of salar composition dispersion with bromide concentration [Salar of Uyuni, Risacher & Fritz, 1999].

5. Other potential lithium resources and geological origins

Apart from spodumene, lithium carbonate can stem from other ores also contained in pegmatite rocks. These contain 1–6% Li wt. and are called amblygonite, eucryptite, lepidolite, petalite, or zinnwaldite. Thanks to high iron content, petalite is particularly employed to manufacture glass. Lepidolite was one of the first ores to be exploited for marginal uses like lithium salts production and specialty glass fabrication but then it slowly lost importance on the market due to high fluorine content. Although the mining phase is common to spodumene exploitation, the great variety of lithium-holding hard-rock minerals illustrated by differences in terms of composition, hardness, and lithium content (Table 3 [32]) denotes an intrinsic limitation for any industrial utilization because new processes need to be developed individually for each ore, with another great variety of by-products.

The aforementioned discrepancies plus the belt-like aspects of pegmatite deposits find their origin in the fascinating geological mechanisms which led to pegmatite formation. Pegmatite comes from the Greek word *pegma* standing for "congealed", "hardened". It has a granite-like composition for it stems from granite magmatic waters, i.e. liquids that remain after the granitic magma crystallization. 450 million years ago, when the terrestrial magma was

Table 3
Characteristics of lithium-rich pegmatite hard-rock minerals.

Name, formula	Li content (wt.%)	Color	Hardness	Density
Spodumene $LiAlSi_2O_6$	3.73	Grayish white, pink, violet, emerald green, yellow	6.5–7	3.1–3.2
Petalite $LiAlSi4O_{l0}$	2.09	Colorless, gray, yellow, yellow gray, white	6–6.5	2.39–2.46
Amblygonite (Li,Na)$AlPO_4$(F,OH)	3.44	White, yellow, gray, bluish gray, greenish gray	5.5–6	2.98–3.11
Lepidolite K$(Li,Al)_3(Si,Al)_4O_{1D}(F,OH)_3$	3.58	Colorless, gray white, lilac, yellowish, white	2.5–3	2.8–2.9
Zinnwaldite $KLiFe^{2+}Al(AlSi_3)O_{10}(F,OH)_2$	1.59	Light brown, silvery white, gray, yellowish white, greenish white	3.5–4	0.9–3.1
Eucryptite $L1AlS1O_4$	5.51	Brown, colorless, white	6.5	2.67

Lithium occurrence [32].

cooling down, the molten magma heated at 400–700 °C made his way through the crust to the surface by seeping through the faults and rifts of the already cooled and hardened blocks of granite. By getting infiltrated inside or in contact with granitic plutons and shields, it was enriched with the most diffusive granite minerals (e.g. rare earth elements; alkaline metals like lithium, rubidium, and cesium) and formed pegmatite pockets, veins, seams, and cordons that spread around and radially from the granitic block they escaped from before hardening (Fig. 7).

Aside granite-bordering pegmatite hard-rock minerals, lithium can also be found in two “soft”-rock silicates also called evaporates for they are assumed to result from salar evaporation and sedimentation: hectorite is a white soft greasy clay whereas jadarite comes in white chalk-like powder-aggregate form. Salt lake brines and evaporates result from the complex geological mechanism of endorheism based on the hydrological closure of freshwater or seawater areas. These newly formed retention and drainage basins were enriched with minerals through the bleaching and dissolution of the bordering rocks. Two different phenomena led to their current aspect: sedimentation, resulting from the deposition of non-drained alluvia carried along by rainfalls; evaporation, resulting from combined effects of sun and wind. Hectorite is by the way a special case of evaporite since it is assumed to originate from the alteration of volcanic ash and tuff into alkaline lakes which were confined and heated by hot springs.

Last but not least, lithium can be extracted deep in the ground from geothermal and oilfield brines. Contained in water pockets and saline aquifers, these brines were enriched with lithium at the contact with underground granitic massifs. As it could be an energy-free by-producing technology, for their main goal is to produce heat and electricity and respectively oil and gas, lithium extraction from such resources stands out very promising. On the one hand, new processes were found to eliminate silica from geothermal fluids, silica being a major ordeal as a source of scaling and corrosion of the circuits; on the other hand, oilfield-based lithium extraction gives the opportunity for oil industry to find an unprecedented interest in EVs, which may help unlocking EV industry and market.

Now that we have depicted the whole structure of lithium industry and listed all kinds of resources, it is time to analyze at the planet scale the global availability and the local repartition of these resources.

6. Resources inventory, geographic distribution and geostrategic implications

The total amount of world lithium resources was already assessed by some researchers, organizations or firms who actually did not reach an agreement neither on figures nor on the way to calculate them (Table 4 [24]). In 2005, the United States Geology Service (USGS) stated that there were some 15 million tons (Mt) of lithium reserve base and 6.8 Mt of reserves. In 2008, Clarke and Harben [25] mentioned 39.4 Mt of resources and 27.7 Mt of reserve base. The global resource estimate is indeed stated in terms of several different quantities: “resource”, “reserve base”, and “reserves”.

The resource is the gross concentration of lithium occurring naturally in the Earth’s crust with a form and amount that make it currently or potentially feasible to extract. Reserve base is the part of lithium resource that meets specified physical and chemical criteria related to mining and production practices (e.g. grade, quality, thickness, and depth). As such, it is the in situ demonstrated (measured plus indicated) resource from which reserves are estimated. It includes the resources that are currently economic (reserves), marginally economic (marginal reserves), and even currently subeconomic (sub economic resources). The reserve is the part of reserve

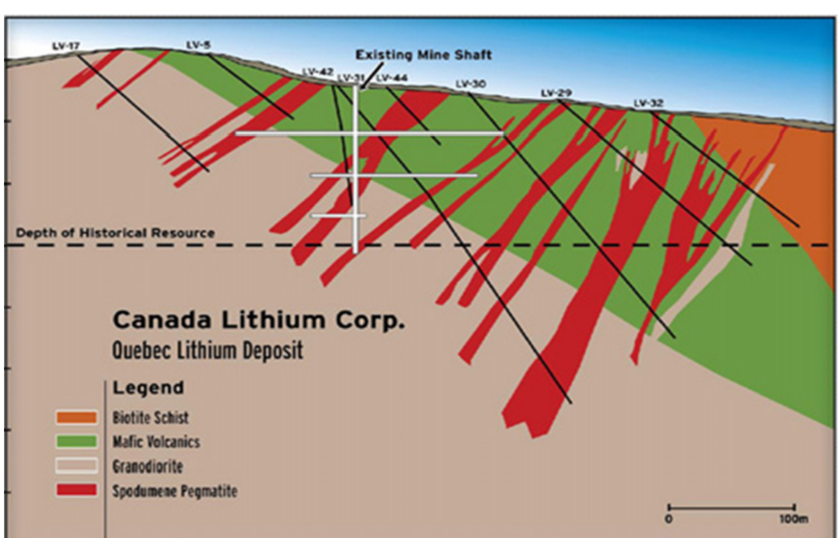

Fig. 7. Sectional view of Quebec Lithium deposit and mine project [Canada Lithium Corp.].

Table 4
Comparison of lithium resource estimations amid bibliographic references.

Li resources	Deposits included	References	Li reserves	Deposits included	References
19.2	15	Tahil [22]	4.6	11	Tahil [22]
25.5	8*	USGS [26]	9.9	8*	USGS [26]
29.9	24	Evans [5,6]	29.4	40	Yaksic and Tilton [23]
64.0	40	Yaksic and Tilton [23]	39.4	61	Clarke and Harben [25]**

Gruber and Medina [24].
* USGS lists information by country, not deposits.
** Clarke & Harben define their estimate as 'broad-based reserves'.

base which could be economically extracted or produced at the time of determination. Extraction facilities are not necessarily in place and operative.

When synthesizing all the available data and adding to them new ones about recently found deposits, mostly in China and Russia, we found out that there were between 37.1 Mt and 43.6 Mt of lithium-rich resources (Table 5). Amidst all of them, 62% consist of brines and 38% of rock minerals. The recent discoveries however mostly concern rock deposits.

When compared to the lithium specific needs of an EV LIB, those 37.1–43.6 Mt of lithium (=197.4–231.9 Mt of Li_2CO_3) appear to guarantee resources for a maximum of 12.3–14.5 billion electric vehicles, i.e. ten times the current world number of automobiles. Although we are now talking about resources, not about reserve base and reserves, this is a very reassuring figure that comforts us in the idea that there is globally enough lithium on Earth to supply the EV market with LIBs.

Considering a global figure makes sense when you want an order of magnitude of the potential market extent. But if you need to compare it to the concrete consumption of end-users like the EV industry, regional influences may have a great importance in a context of free market and competitiveness.

In this respect, it is interesting to examine lithium resources geographic distribution (Fig. 8). The biggest amount of lithium is located in the ABC triangle made by Argentina, Bolivia, and Chile. With 43.6% of presence in this part of the world, lithium mostly comes from salt lake brines available in South America. North America and Australasia represent almost all the rest of the resources shares with around 25% for each. Although it is expected to become one of the world biggest lithium end-users, for many car manufacturers openly involved in EVs are settled in Germany, the UK, and France, Europe appears to be the poor relation to lithium owners world ranking with less than 3% of resources.

As far as brines are concerned, those lying in North America come from geothermal and oilfields whereas those located in China are all salt lakes. As a whole, brines resources are very concentrated in places far from the usual centers of consumption, except in some places of United States and Canada. Rock minerals resources are way more homogeneously distributed on Earth with deposits located on each continent. But still, only a few sites are currently producing in Canada, Australia and China.

From such information display, we can infer that the distribution of lithium resources is very polarized and a great trade imbalance is to be expected in the near future. It will be all the more the case since some of the producing countries are sensitive areas susceptible to nationalize lithium exploitation (e.g. Bolivia) or likely to have coordinated actions on lithium prices, for example through a hypothetical "organization of lithium-exporting countries". Europe will be the greatest victim of this geostrategic bottleneck for she is the expected first-rank consumer of lithium but has more or less no resource. South America will obviously come out on top in this lithium deal for its lack of inner consumption will turn her into a full exporter of a low-cost salt-lake brine-based lithium carbonate. Australia, Asia, and North America will presumably have a balanced trade between their production and own need. The vicinity of Russian hard rock minerals deposits will be a matchless advantage for

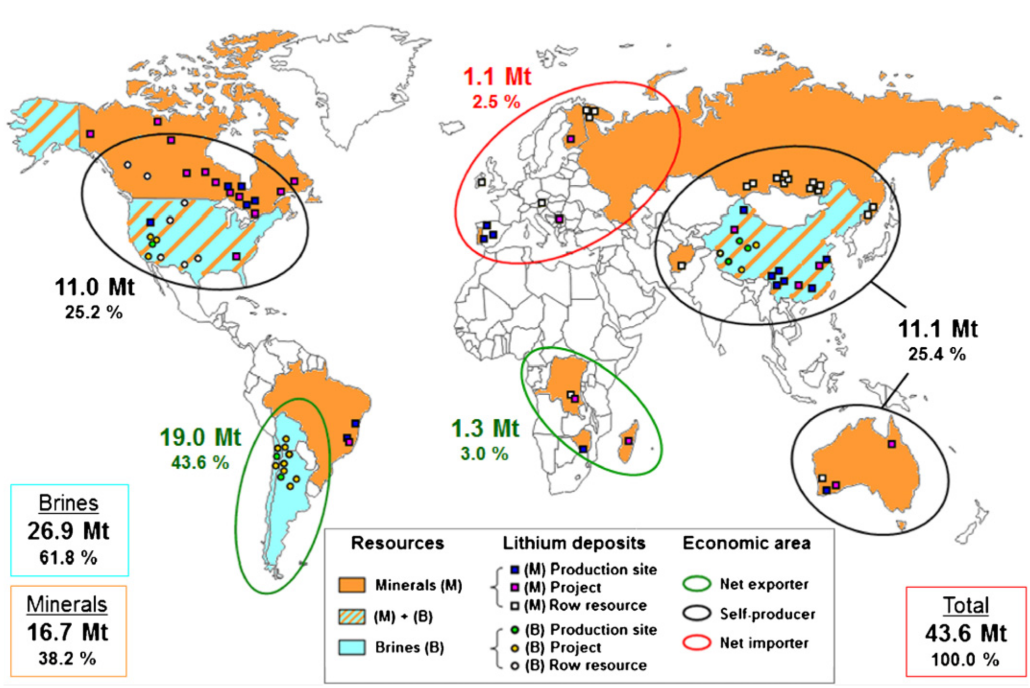

Fig. 8. Map of lithium resource availability and geostrategic impacts [own works on a base map by Daniel Dalet].

Table 5
Inventory of minerals and brines known deposits [own works].

Country	Deposit	Type	Min (kt)	Max (kt)
USA	Kings Mountain Belt	MPS	5,450	5,450
Serbia	Jadar Valley	MEJ	953	990
RDC	Manono	MPS	835	835
Australia	Greenbushes Mine	MPS	560	560
China	Gajika	M	560	591
China	Yichun	MPL	325	513
RDC	Kitotolo	MPS	310	310
Russia	Kolmozerskoe	M	288	844
China	Jiajika	MPS	240	480
China	Maerkang / Barkam	M	220	225
Canada	Quebec Lithium	MPS	163	365
Russia	Goltsovoe	M	139	288
Russia	Polmostundrovskoe	MPS	139	363
Russia	Ulug-Tanzekskoe	M	139	288
Russia	Urikskoe	M	139	288
China	Daoxian	MPL	125	182
USA	Kings River Valley / Caldera McDermitt	MSH	114	2,000
Austria	Koralpe	MPS	100	100
Brazil	MIBRA	MP	100	100
Zimbabwe	Bikita	MPP	57	168
China	Lijiagou	MP	53	53
Canada	Separation Rapids / Big Whopper	MPP	50	72
Russia	Achivansky (Uchastok)	M	46	46
Russia	Belorechenskoe	M	46	46
Russia	Etykinskoe	M	46	46
Russia	Orlovskoe	M	46	46
Russia	Pogranichnoe	M	46	46
Russia	Tastygskoe	M	46	46
Russia	Vishnyakovskoe	M	46	46
Russia	Voronietundrovskoe (Vasin-Mylk)	MPS	46	820
Russia	Voznesenskoe	M	46	139
Russia	Zavitinskoe	M	46	139
China	Hupei	MP	42	42
Canada	Moblan	MPS	37	37
Canada	Gods Lake / Godslith Lithium	MPS	25	25
Brazil	Cachoeira	MP	23	23
Canada	Bernic Lake / Bird River Greenstone Belt	MPS	19	19
Canada	Moose 2	MPS	16	16
Portugal	Mesquitila / Guarda	MP	10	10
Canada	Niemi Lake	MPS	1	1
MINERALS		***M***	***11,693***	***16,659***

Country	Deposit	Type	Min (kt)	Max (kt)
Afghanistan	Helmand Basin	MPS	-	-
Afghanistan	Katawaz Basin	MPS	-	-
Canada	Big Bird, Curlew	MPS	-	-
Canada	English River Greenstone Belt	MPS	-	-
Canada	McAvoy	MPS	-	-
Canada	Separation Rapids / Big Mack, Zone 11	MPP	-	-
China	Jinchuan	MP	-	-
China	Ningdu	MP	-	-
Russia	Alahinskoe	M	-	-
Russia	Belo-Tagninskoe	M	-	-
Russia	Bolchoï Potchemvarek	M	-	-
Russia	Diturskoe	M	-	-
Russia	Knyazheskoe	M	-	-
Russia	Ohmylk	M	-	-
Russia	Oleniy Hrebet	M	-	-
Russia	Olondinskoe	M	-	-
Russia	Otboïnoe	M	-	-
Russia	Pellapahik	M	-	-
Russia	Podgorskoe	M	-	-
Russia	Raduga	M	-	-
Russia	Severny Vystup	M	-	-
Russia	Tala	M	-	-
Spain	Mina Feli	MP	-	-

Country	Deposit	Type	Min (kt)	Max (kt)
Bolivia	Salar de Uyuni	BS	10,200	10,200
Chile	Salar de Atacama	BS	6,300	6,300
China	Qaidam Basin	BS	2,020	3,300
China	Zhabuye Lake	BS	1,530	1,530
Argentina	Salar del Rincón	BS	1,118	1,118
USA	Brawley	BG	1,000	1,000
Argentina	Salar del Hombre Muerto	BS	800	800
USA	Smackover	BO	750	750
Canada	Beaverhill Lake	BO	515	515
USA	Salton Sea	BG	316	316
USA	Clayton Valley / Silver Peak	BS	300	400
Chile	Salar de Maricunga	BS	220	220
China	DXC / Da	BS	170	181
Argentina	Salar d'Olaroz	BS	156	280
BRINES		***B***	***25,395***	***26,910***
TOTAL			**37,088**	**43,569**

Minerals
16.7 Mt
11.7 Mt

Brines
26.9 Mt
25.4 Mt

TOTAL
43.6 Mt
37.1 Mt

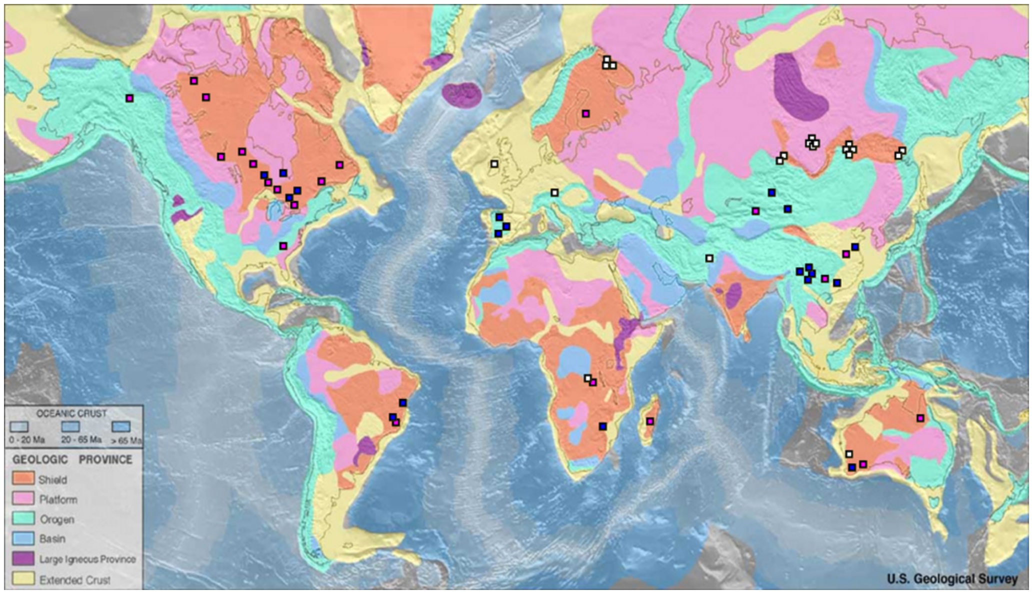

Fig. 9. Match of hard-rock minerals locations with the map of geologic provinces [base map from United States Geological Survey – USGS].

China whose striking advance in EV industry with cars as well as batteries makes it all ready for electromobility. Recent agreements were already signed between both countries at the time of this publication [33].

7. Perspectives and broadening prospects

The synthesis of the current context for lithium industry is now easier. The cheapest lithium extraction is made with salt lake brines, representing the majority of the currently produced lithium carbonate and the majority of the known world resources. Though, those same salt lake brines are geographically concentrated in South America, so they are submitted to geostrategic and geoeconomic bottlenecks. Besides, the process durations of salt lake brines extraction and treatment are very long and inadequate to follow and adapt the production to any short-term increase of the lithium demand. As a result, and independently from the *business as usual* predictive evolution we made before, the most presumable scenario that we can foresee for lithium market is a sudden raise of lithium price to levels that are bound to unblock the yet abandoned, interrupted or non-started projects of hard-rock minerals mining. Once this is done, the following few years will be a difficult transition to a calmer and flatter evolution of lithium price, waiting for the hard-rock mining companies to run their plants.

To avoid or smooth over this difficult transitional period, exploration efforts must be done right now to identify, assess and exploit the two big categories of lithium resources available in nature: on the one part, pegmatite-based resources with hard-rock lithium-containing minerals as well as the geothermal and oilfield brines which got enriched with lithium at their contact, deeply in the ground; on the other part, seawater-based resources with salt lake brines as well as the evaporites soft-rock minerals which are the result of their sedimentation. Given the geological origins of their formation, we looked for possible common ways to identify lithium deposits and we found the following results.

When superposing the pegmatite-based hard-rock deposits site locations on the map which displays the various world geologic provinces, almost all of them appear located on or at the fringe of cratons, i.e. old and stable parts of the continental crust, mainly

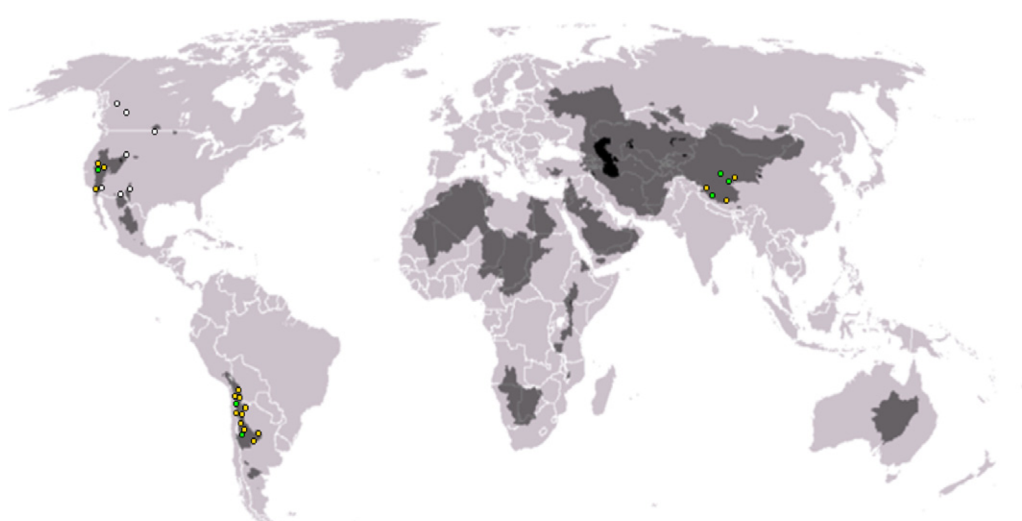

Fig. 10. Map of endorheic basins and matching with salt lake brines locations [base map from Wikipedia, "Endorheic basin"].

made of granitic plutons (Fig. 9). Cratons can be described as shields, in which the basement rock crops out at the surface, and as platforms, in which the basement is overlain by sediments and sedimentary rock. Both parts are susceptible to host deposits of lithium-rich minerals; the difference will only be the difficulty to access them. The same observation was done with the map of endorheic basins (Fig. 10), would they be at the surface like any lake or under the ground like oilfield saline aquifers. The main difference is that all endorheic basins are not at the same level of evolution and they do not suffer the same environmental conditions; some originate as meteoritic reservoirs, others as magmatic ones. Their exploration and validation as viable lithium deposits will thus be more difficult and harder than that of pegmatite hard-rock minerals. Concerning geothermal and oilfield brines, their potential and location are already known everywhere where wells were drilled either to exploit geothermic energy or to pump out oil and gas.

In any case and to sustain the ecological characteristic of EVs, the mining, extraction and treatment processes which are and will be at the origin of lithium production and sales must guarantee a level of carbon and pollution impact as low as possible, below the pollution levels that we are now imposing through the daily use of ICE-vehicles. The EV industry already has to cope with potentially varying carbon contents for the electricity about to feed future EVs; it would thus be in good taste if lithium extraction would add no other further limitations.

8. Conclusion

Along with the boom of lithium-ion batteries, the technological breakthrough of electric vehicles brings about many questions and doubts, especially as regards the availability and price evolution of lithium. Though many lithium-based products are used by other market sectors, the current state of resources shows that there is no danger for the planet to run out of lithium. Besides, even a forecast fivefold increase of lithium price would not impact the price of battery packs. But still, lithium shortages could threaten the EV market supply since the most directly available resources are currently geographically concentrated. Moreover, the scale adaptation of current production facilities appears not reactive enough to follow in real-time a highly probable steep growth in lithium demand. Creating strategic stocks, signing long-term supply contracts and exploiting in an environment-friendly way the unexplored lithium-rich brines and ores deposits thus stand out as sine qua non conditions for the EV industry to exist and last sustainably.

Acknowledgements

This work was financially supported by the Atomic Energy and Alternative Energies Commission (CEA, France). We wish to thank Sophie Avril and the anonymous reviewers for their useful comments.

References

[1] Nicholson P, Evans RK. Evaluating new directions for the lithium market. Journal of Minerals 1998;50(May (5)):27–9.
[2] Evans RK. Lithium reserves and resources. Energy 1978;3(June (3)):379–85.
[3] Evans RK. Western world lithium reserves and resources, The Institute of Metals, Aluminium-Lithium Alloys III. In: Proceedings of the 1985 conference. 1986.
[4] Evans RK. The current status of the lithium business. Golden, CO: Internal Communication, Amax Mineral Resources Company; 1988.
[5] Evans RK. An abundance of lithium; March 2008. http://www.che.ncsu.edu/ILEET/phevs/lithium-availability/An_Abundance_of_Lithium.pdf.
[6] Evans RK. An abundance of lithium: part two; July 2008. http://www.evworld.com/library/KEvans_LithiumAbunance_pt2.pdf.
[7] Kunasz IA. Lithium how much? Foote Prints 1980;48(1):23–7.
[8] Kunasz IA. Reservas mundiales de litio. In: El litio, un Nuevo recurso para Chile; 1986. p. 33–43.
[9] Kunasz IA. Lithium resources. In: Industrial minerals and rocks; 1994. p. 631–42.
[10] Anstett TF, Krauss UH, Ober JA, Schmidt HW. International strategic minerals inventory report—lithium. United States Geological Survey (USGS) circular 930-I; 1990.
[11] Andrews HJ. The industry of lithium. Lithium Division, La Paz: FMC Corporation; 1991.
[12] Ober JA. Lithium, USGS minerals yearbook; 1994–2006.
[13] Kingsnorth D. Overview of lithium market. Curtin Univ. of Tech., Sons of Gwalia Limited; 2001.
[14] Mora M.Análisis de la estructura mundial de la industria del litio y criterios de priorización de proyectos de investigación científica y tecnológica. 2003.
[15] Jimenez D. oral presentation on lithium industry. In: Industrial minerals conference. 2003.
[16] Ebensperger A, Maxwell P, Moscoso C. The lithium industry: its recent evolution and future prospects. Resources Policy 2005;30:218–31.
[17] Roskill. The economics of lithium. 11th ed; 2009.
[18] Hammond AL. Research news: lithium: will short supply constrain energy technologies? Science 1976;191:1037–8.
[19] Fasel D, Tran MQ. Availability of lithium in the context of future D-T fusion reactors. Fusion Engineering and Design 2005;75-79:1163–8.
[20] Will FG. Impact of lithium abundance and cost on electric vehicle battery applications. Journal of Power Sources 1996;63(November (1)):23–6.
[21] Tahil W. The trouble with lithium. Implications of future PHEV production for lithium demand. Meridian International Research; January 2007.
[22] Tahil W. The trouble with lithium 2. Under the microscope. Meridian International Research; May 2008.
[23] Yaksic A, Tilton JE. Using the cumulative availability curve to assess the threat of mineral depletion: the case of lithium. Resources Policy; 2009.
[24] Gruber P, Medina P. Global lithium availability: a constraint for electric vehicles? University of Michigan; April 2010.
[25] Clarke GM, Harben PW. Lithium availability WallMap (LAWM®); 2008.
[26] Lithium statistics, USGS; 2010.
[27] Hocquart C. Rare earths (REE), IFRI energy breakfast roundtable, Brussels; May 20, 2010.
[28] Committee of French car manufacturers (CCFA); 2011. http://www.ccfa.fr/IMG/pdf/tdb26.pdf.
[29] Lithium and lithium compounds. Wiley; 2000.
[30] Risacher F, Fritz B. Quaternary geochemical evolution of the salars of Uyuni and Coipasa, Central Altiplano, Bolivia, Chemical Geology. Elsevier Science Publishers; 1991.
[31] Miyai Y, Ooi K, Katoh S. Recovery of lithium from seawater using a new type of ion-sieve adsorbent based on $MgMn_2O_4$. Separation Science and Technology 1988;23(1–3):179–91.
[32] Lithium occurrence, Institute of Ocean Energy, Saga University, Japan, retrieved 2010-12-10. http://www.ioes.saga-u.ac.jp/ioes-study/li/lithium/occurence.html.
[33] The Russian Corporation of Nanotechnologies (RusNano) and Thunder Sky Group Limited (China) have signed a joint venture agreement for the first Russia-based production of high-capacity LIBs.